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STUDY OF MODEL MATCHING TECHNIQUES FOR THE
DETERMINATION OF PARAMETERS IN HUMAN PILOT MODELS

REPORT ON TASK 4

TWO-AXIS MODEL

8426-6005-RU-000 6 April 1964

Prepared under Contract NAS 1-2582
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ABSTRACT

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This report describes the results of applying continuous model matching techniques to the determination of parameters of a human operator in a two-axis tracking task. The work constitutes the fourth and final task of a study of model matching techniques being conducted under NASA Contract NAS 1-2582.

The report presents the approach used in extending model matching to the more complex situation of two-axis tracking where at least eight unknown parameters must be obtained. A separation into sequential computer analysis of each of the two axes of operation is shown to be feasible, and sets of parameters for each axis are obtained. The use of this technique for detecting the existence of cross-coupling terms between the operator's responses and to determine the cross-coupling coefficients quantitatively is of particular interest. This work was conducted with a relatively small amount of analog computing equipment.

Author

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1. INTRODUCTION

The objective of the research conducted under Task 4 was to extend the model matching approach developed under the single-axis studies (Ref. 1, 2, 3) to the more complex and unexplored conditions of two-axis tracking. To obtain a maximum of useful information in the available time the effort was restricted to applying the continuous model matching techniques used in Tasks 1, 2, 3 to mathematical models of limited complexity excluding and including simple cross-coupling terms. The application of the technique to more than two axes of manual control was not within the scope of this research but can be considered to be a direct extension along the lines presented in this report. The complexity of such model matching operations is correspondingly greater but not prohibitive.

The model matching effort was applied to the task of controlling a linear, symmetrical and essentially uncoupled two-axis dynamic system, using an integrated display of two error components on one oscilloscope screen. An integrated two-axis fingertip controller was used for manipulating the two control channels simultaneously. The simplification of the two-dimensional tracking task by the provision of an integrated display and an integrated fingertip controller has the side effect of causing small amounts of random cross-coupling in the operator's response as will be discussed in Sections 2 and 5. The ability of the model matching technique to detect such effects and to determine them quantitatively will be demonstrated in this study.

In order to gain greater insight into the nature and validity of the model matching results the mean squared residual error was systematically investigated as a criterion of "accuracy of fit." The mean squared tracking error in each control channel was also considered in order to compare and assess the operators' tracking performance in these channels. To acquire meaningful and consistent tracking data it was found essential to assure an adequate learning period for the test subjects.

The report presents basic considerations pertaining to the formulation of two-axis operator models; a summary of the experimental procedure and the analog computer programming; a discussion of the experimental results obtained; and some conclusions and recommendations for future research.

2. FORMULATION OF A TWO-AXIS MODEL OF THE HUMAN OPERATOR

2.1 Extension of Single-axis Model

A straightforward approach to formulating a two-axis model of the human operator for the purposes of this study is to make a direct extension of the single-axis model used previously (Reference 1). A symmetrical two-axis tracking task was selected in which the excursions of the controlled element are assumed independent of each other (uncoupled). The same linear, time-invariant second order dynamics as in Task 1 of the study is assumed for both axes of the system (see Section 3). The error terms of the two channels are displayed as vertical and horizontal deflections, x_v and x_h, of a dot on an oscilloscope screen (cartesian coordinates). The operator performs a compensatory tracking task in two dimensions by trying to null the displayed error vector.

For a direct extension of the previous work it is a reasonable first step to characterize the human operator's response to vertical and horizontal error signals in terms of two uncoupled, second order linear differential equations,

vertical axis :

$$\ddot{y}_v + a_{1v}\,\dot{y}_z + a_{2v}\,y_v = a_{3v}\,x_v + a_{4v}\,\dot{x}_v$$

horizontal axis : (2.1)

$$\ddot{y}_h + a_{1h}\,\dot{y}_h + a_{2h}\,y_h = a_{3h}\,x_h + a_{4h}\,\dot{x}_h$$

In accordance with earlier notation the model differential equations used to match the human operator output y_v, y_h are written in terms of z_v and z_h with unknown coefficients α_{iv} and α_{ih}, e.g.

$$\ddot{z}_v + \alpha_{1v}\,\dot{z}_v + \alpha_{2v}\,z_v = \alpha_{3v}\,x_v + \alpha_{4v}\,\dot{x}_v \qquad (2.2)$$

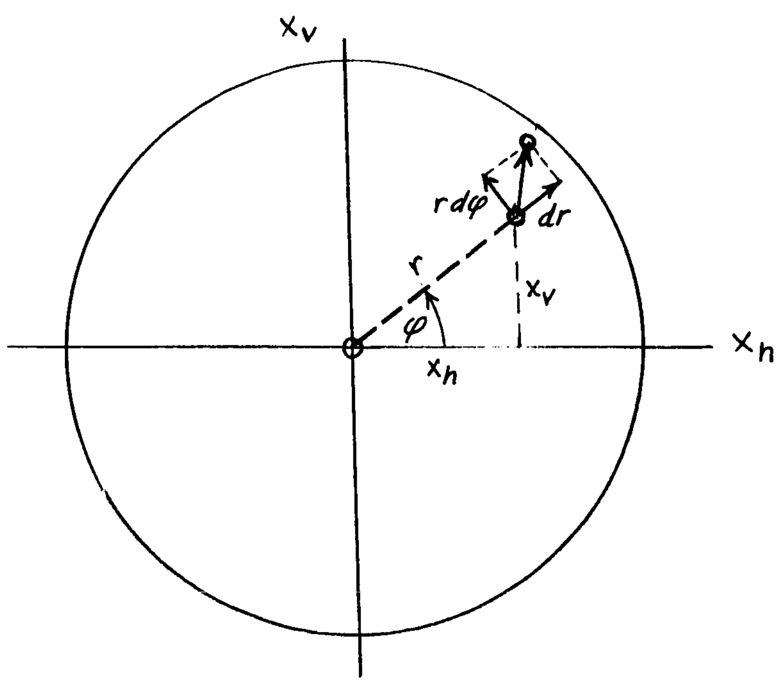
(The subscripts v and h will be omitted in subsequent sections where no misunderstandings can arise.)

Since the controlled element dynamics does not contain cross coupling between axis, the operator's responses in each axis can be assumed as essentially independent. This initial assumption is supported by the results of a symmetrical two-axis tracking experiment conducted by Humphrey (Reference 4). However, the possibility of cross-coupling in the operator's responses must also be considered.

2.2 Cross-coupling Effects

The integrated display of two tracking error components on one display screen, and the integration of two-axis control into a single fingertip controller introduces a problem in the interpretation by the operator of visual stimuli and kinesthetic feedback. When observing the displayed tracking error in two dimensions the operator probably does not consciously resolve the error vector into cartesian coordinates, x_v, x_h, in order to manipulate the control stick accordingly. He may actually interpret the display error and the stick deflection in terms of polar coordinates (see sketch below). The displacement element expressed in polar coordinates r and φ is obtained by linear transformation of the cartesian elements dx_v, dx_h as follows:

$$\begin{aligned} dr &= dx_h \cos\varphi + dx_v \sin\varphi \\ r d\varphi &= dx_h \sin\varphi + dx_v \cos\varphi \end{aligned} \tag{2.3}$$



Resolution of Coordinate Changes on Display

The operator could not perform this resolution (or its inverse) with any precision even if he knew the individual deflection elements. This suggests that there are interactions in his responses to perceived stimuli regardless of whether they are perceived in terms of cartesian or polar coordinates. A further complication stems from the fact that a fingertip controller of the type used in this study does not provide a clear "kinesthetic" feedback of stick deflections in the horizontal or vertical sense. Hence the operator's control deflections in the two axes contain inevitable interactions.

2.3 Mathematical Model of Cross-coupling Effects

On the basis of these considerations it is reasonable to expect unintentional cross-coupling of varying degree to exist in the tracking responses of the operator. The model equations (2.1),(2.2) should therefore be modified as follows:

vertical:

$$\begin{aligned} &\ddot{z}_v + \alpha_1 \dot{z}_v + \alpha_2 z_v + \underline{\beta_1 z_h + \beta_2 \dot{z}_h + \gamma_1 z_v z_h} \\ &= \alpha_3 x_v + \alpha_4 \dot{x}_v + \underline{\beta_3 x_h + \beta_4 \dot{x}_h + \gamma_2 x_v x_h} \end{aligned} \tag{2.4}$$

and similarly for the horizontal channel. The additional underlined terms on the left and right hand sides of the equation are the various cross-coupling effects under discussion having unknown coefficients β_i and γ_i.

The following distinction is made as to the sources and form of the various cross-coupling terms added to the equation: The effects of the excitation signal x_h or its derivative will be termed <u>perceptual</u> or input cross-coupling. The effects of the variable z_h will be termed <u>motor</u> or output coupling. The terms may appear in linear or nonlinear form. The latter case represents conditions where a heavy task load occurs simultaneously in both channels and causes a deterioration of control action with unintentional response in the wrong channel. The coefficients β_i, γ_i are used to denote these different coupling phenomena as follows:

	Output (Motor)	Input (Perceptual)
Linear	β_1, β_2	β_3, β_4
Nonlinear	γ_1	γ_2

As will be discussed in Section 5 some experimental computer runs were included in this study to detect the presence of cross-coupling in the operators' performance and to observe, if possible, a quantitative improvement in model matching by the introduction of various cross-coupling terms.

For further study of these phenomena it would be of great interest to introduce artificial display cross-coupling, e.g.

$$x_v' = x_v + m_1 x_h \tag{2.5}$$

$$x_h' = x_h + m_2 x_v$$

and to retrieve the coefficients m_1, m_2 in the operator's response by model matching techniques. It would also be of considerable practical value to study control tasks which are essentially asymmetrical and exhibit inherent coupling phenomena. Such tasks probably tend to induce reverse cross-coupling in the operator's responses after the operator has learned to cope with this situation. The present study did not permit further pursuit of these interesting problems for lack of available time.

3. EXPERIMENTAL PROCEDURE

3.2 Description of the Tracking Task

The human operator tracking task was basically a combination of two single axis tasks of the form described in Reference 1. A single oscilloscope having a 5 inch reticle calibrated in 1 centimeter units was used for the display. The operator manipulated a two-axis control stick. This hand controller has been used previously for the performance of single axis tracking studies in Tasks 1, 2, 3. A block diagram of the two-axis control system is illustrated in Figure 1.

Two uncorrelated random excitation signals r_v and r_h activating the vertical and horizontal channels, respectively, were generated by two separate noise generators, each having the zero-frequency spectral density $N_o \doteq 2.41$ volts^2/cps and a flat power spectrum from zero to approximately 100 rad/sec. The input signals to each channel were obtained by passing each noise signal through a filter having the transfer function

$$\frac{40}{(4s+1)^2} \qquad (3.1)$$

The dynamics of the controlled element were identical for the two channels and were characterized by

$$\frac{10}{s(s+1)} \qquad (3.2)$$

The channels were uncoupled. The displayed quantities x_v (vertical deflection on the scope) and x_h (horizontal deflection) as well as the operator's output signals y_v (control stick vertical position, normalized in terms of full stick deflection) and y_h (control stick horizontal position) were recorded on magnetic tape for repeated use throughout the study. Sufficiently many tracking runs were performed to study the feasibility of the model matching techniques, but no attempt was made to provide an extensive coverage of operator characteristics. The parameter values found therefore do not attempt to give a broad, statistically

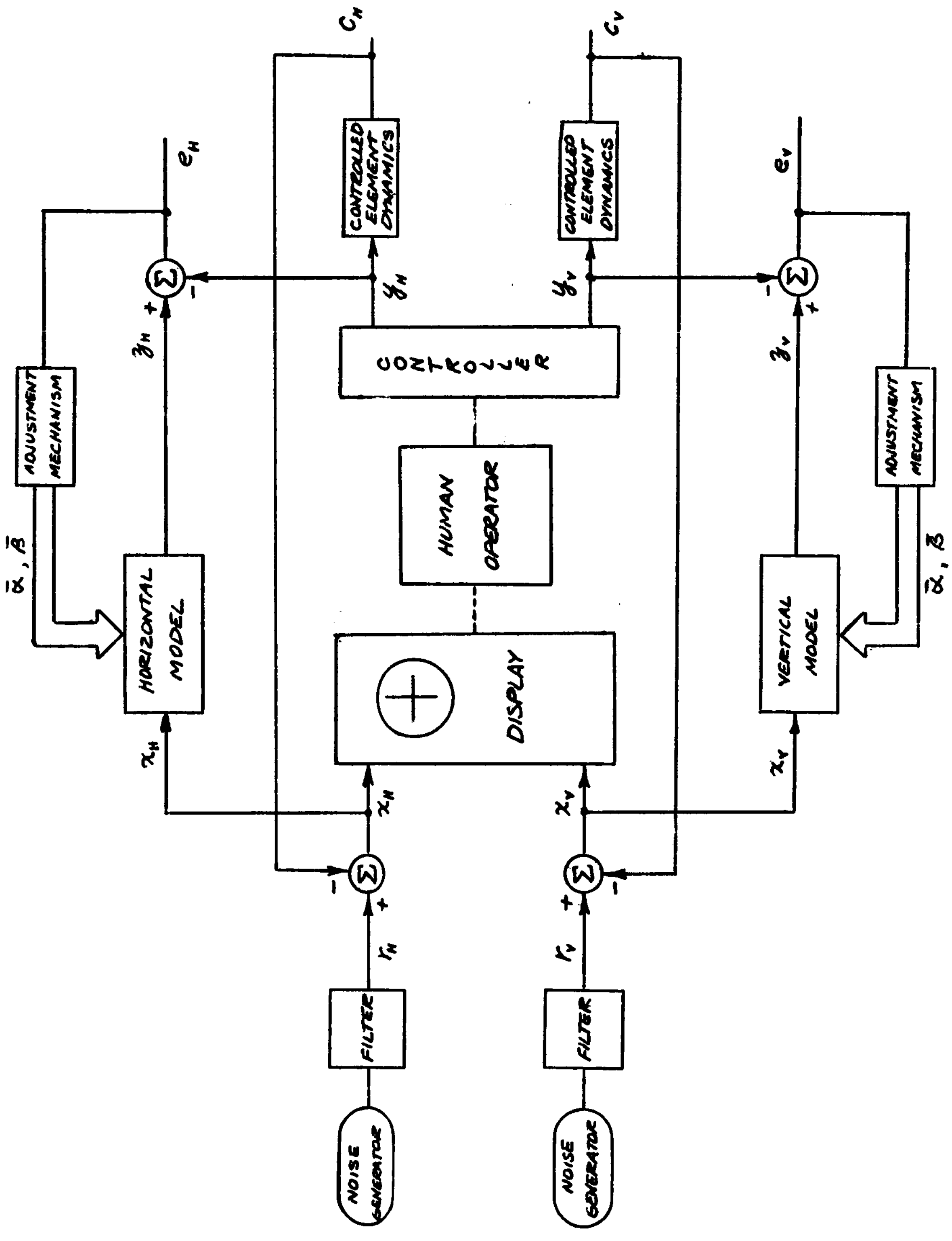


Figure 1. Block Diagram of Two-axis Control System

significant picture of operator performance.

Two human operators performed three tracking tasks each with three replications. The three tasks were: 1) single axis tracking in horizontal direction, 2) single axis tracking in vertical direction, 3) two-axis tracking. All runs were of 5 minutes duration. The mean squared values of excitation signals, $\overline{r_h^2}$ and $\overline{r_v^2}$, displayed errors $\overline{x_h^2}$ and $\overline{x_v^2}$, and operator output, $\overline{y_h^2}$ and $\overline{y_v^2}$ were recorded for each run.

3.2 Operator Instructions and Training

In order to obtain approximately invariant tracking performance, the two subjects were given extensive training sessions both in single-axis and two-axis tracking before any data were recorded. After proficiency and consistent performance in one axis tracking had been demonstrated, an additional period of one hour (12 five-minute tracking runs) was devoted to training in the two-axis task. The importance of adequate training was pointed out and quantitatively demonstrated in a two-axis tracking study by Humphrey (Reference 4). The operators were instructed to achieve and maintain minimum display error, as measured by the distance between the dot and the center of the scope. They were also instructed to avoid excessively large and rapid control stick deflections as much as possible. Data taking was initiated only after the operators had acquired reasonable tracking proficiency.

3.3 Determination of Human Operator Model Parameters

A mathematical model was fitted to the human operator data by means of the continuous method described in previous task reports (References 1, 2). Data obtained from two-axis tracking was analyzed separately and model matching was performed individually for each of the two channels. Repeated model matching runs of the same recorded data were required in some instances to minimize interactions between parameter adjustments which occurred when starting from arbitrarily chosen initial parameter settings. After one or two iterations performed in this manner, sets of parameters were obtained which exhibited only minor fluctuations during the run. This procedure was found necessary to provide dependable parameter values for subsequent evaluation of the effect of adjustment gains, damping terms, and cross-coupling terms on the model matching performance.

In order to be able to evaluate the adequacy of the model, the mean squared residual matching error,

$$\overline{e^2} = \frac{1}{T}\int_0^T e^2\,dt \tag{3.3}$$

was used as a "matching accuracy criterion." In this equation, e is the matching error, z - y, and T is the length of the tracking run.

During the search for cross coupling terms β in the model (see Equation 2.4) the coefficients α were held fixed to avoid interaction between the adjustment loops for the α_i and β_j. The model parameters of the uncoupled system were thus held near their optimum values during attempts of finding a further improvement of the matching criterion by the introduction and adjustment of various cross-coupling terms.

The off-line procedure described above involving the repeated use of taped operator tracking data was necessary(1) in order to minimize computational complexity and (2) to provide greater assurance of deriving meaningful values of the different matching criteria introduced in this study. This point will be further discussed in Section 5 in terms of the model matching results presented there.

4. ANALOG COMPUTER PROGRAMMING

To determine the coefficients α_i, β_i, γ_i... of the postulated two-axis model of the human operator it is possible to use the continuous model matching technique previously developed in connection with single-axis tasks. Clearly, it will not be feasible to obtain all model parameters simultaneously as was explained in Task Reports 2 and 3 (Ref. 2, 3). The dynamic interaction effects of the many adjustment loops (numbering at least eight) would tend to cause too much drift, perturbation and even instability in individual parameters. For the purpose of this study a restriction to the parameters of one operator "channel" at a time provided a reasonable simplification, reducing the number of unknown parameters to 4 in the absence of coupling terms in the model.* Coupling terms were introduced, one at a time, while the coefficients of uncoupled terms α_i, in the model equation were held fixed at the optimum levels established by previous model matching runs. In this manner the entire sequence of model matching experiments based on tape-recorded two-axis human tracking data can be completed with a relatively limited amount of computing equipment.

To reduce the number of sensitivity equations per control channel to be implemented simultaneously on the computer, recourse was taken to the approximations discussed in Task Reports 2 and 3. This permits the generation of the parameter influences u_1 and u_2 by one computer circuit, and u_3 and u_4 by a second circuit. By suitable reprogramming it is even possible to eliminate the second parameter influence circuit altogether and to obtain u_3 and u_4 from the circuit which yields the output variable z_1 in a manner similar to that used by Adams (Reference 5). According to Equation (2.2) z is obtained as the result of linear superposition of the two terms $\alpha_3 x$ and $\alpha_4 \dot{x}$. Furthermore, u_3 and u_4 must satisfy the equations

$$\begin{aligned} \ddot{u}_3 + \alpha_1 \dot{u}_3 + \alpha_2 u_3 &= x \\ \ddot{u}_4 + \alpha_1 \dot{u}_4 + \alpha_2 u_4 &= \dot{x} \end{aligned} \qquad (4.1)$$

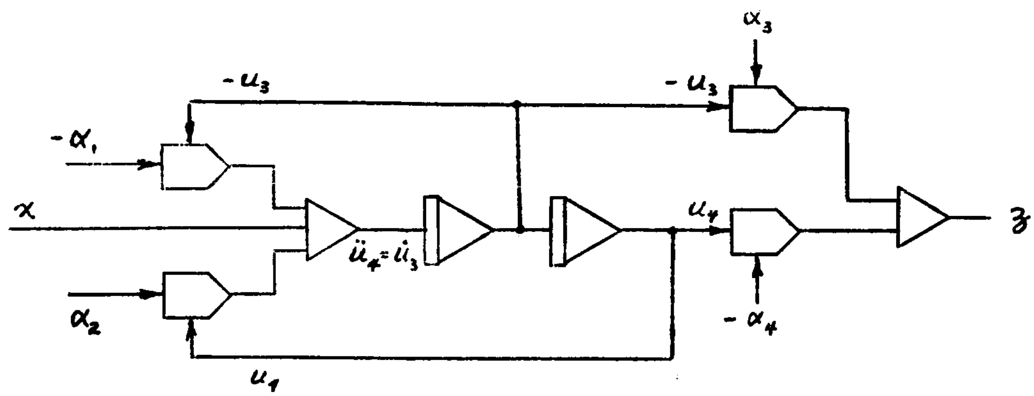
---

* Note that separation of the model matching operation into 2 single-axis operations is justifiable since two distinct error criteria $f_v = \frac{1}{2}(e_v + q\dot{e}_v)^2$ and $f_h = \frac{1}{2}(e_h + q\dot{e}_h)^2$ have to be minimized individually.

Therefore,

$$z = \alpha_3 u_3 + \alpha_4 \dot{u}_4 \qquad (4.2)^*$$

The corresponding computer circuit is shown in the figure below.



Simplified Computer Circuit for z, u_3 and u_4

The computer program for finding the parameter influences of cross-coupling terms β_1, β_2, ... is derived by a simple extension of the above techniques. Using the notation

$$\frac{\partial z}{\partial \beta_3} = u_{\beta 3}$$

it follows from Equation (2.4) that $u_{\beta 3}$ must satisfy the sensitivity equation

$$\ddot{u}_{\beta 3} + \alpha_1 \dot{u}_{\beta 3} + \alpha_2 u_{\beta 3} = x_h$$

---

* This equation omits the effect of initial values which is of no importance from a practical standpoint.

Similar equations yield the parameter influence coefficients $u_{\beta 1}$, $u_{\beta 2}$, etc. To simplify the computer program these coefficients can be obtained from the same parameter influence circuit as u_1, u_2, by switching the forcing function in turn from z_v to x_h, $\dot{x}_h$, z_h, ... etc.

The sensitivity equation for $u_{\gamma 2}$ requires as a forcing function the product $x_v x_h$, while for $u_{\gamma 1}$ a more complicated term $(z_v z_h + \gamma_1 z_h u_{\gamma 1})$ is required.*

*Some simplifying assumptions are made here by ignoring the second-order effects of coupling parameters in one channel upon the sensitivities of coupling parameters in the second channel, and vice versa.

5. RESULTS AND DISCUSSION

5.1 Two-axis Model Matching Results

The results of a typical model matching run are shown in Figures 2 and 3. As outlined in the previous section the computer simultaneously adjusts the four parameters of the linear model

$$\ddot{z} + \alpha_1 \dot{z} + \alpha_2 z = \alpha_3 \dot{x} + \alpha_4 x \qquad (5.1)$$

which represents the input-output characteristics of the human operator in one axis of the two-axis task in the absence of cross-coupling. Figure 2 shows the parameter values obtained when the mathematical model is matched to the horizontal tracking response only. The parameters obtained from matching vertical axis tracking response are shown in Figure 3. The displayed error appears on channel 1 and the pilot's output on channel 3 of these figures. The two traces exhibit a highly consistent tracking behavior, with the frequency and amplitudes of the operator's output not varying significantly during the run. Consequently, it is expected to find that the model parameters maintain approximately constant values. This result can indeed be observed in both Figures 2 and 3 on channels 4 through 8.*

The validity of the model matching results presented in this section will be evaluated by examining the mean squared residual matching error defined by

$$\overline{e_h^{\,2}} = \frac{1}{T}\int_0^T e_h^{\,2}\, dt \qquad (5.2)$$

where e_h is the error obtained by subtracting the model output for the horizontal axis from the pilot's horizontal axis output and T is the run length. Similarly, $\overline{e_v^{\,2}}$ represent the mean squared residual matching error in the vertical axis. The values of $\overline{e_v^{\,2}}$ abd $\overline{e_h^{\,2}}$ obtained for the runs of Figures 2 and 3 are given below in Table I. The table also gives reference values of $\overline{e_h^{\,2}}$ and $\overline{e_v^{\,2}}$ obtained when the model parameters were

*This tracking performance differs substantially from the results obtained by Adams (Reference 6) in a similar two-axis tracking study. Variations in tracking performance and parameter values found in that study indicate that the pilot had not developed an invariant control strategy. Considering the highly complex task described in the experimental procedure of that report, it is expected that an increased training period would eliminate variations of this nature.

Time History of Parameter Adjustment
Pilot R, Vertical Axis

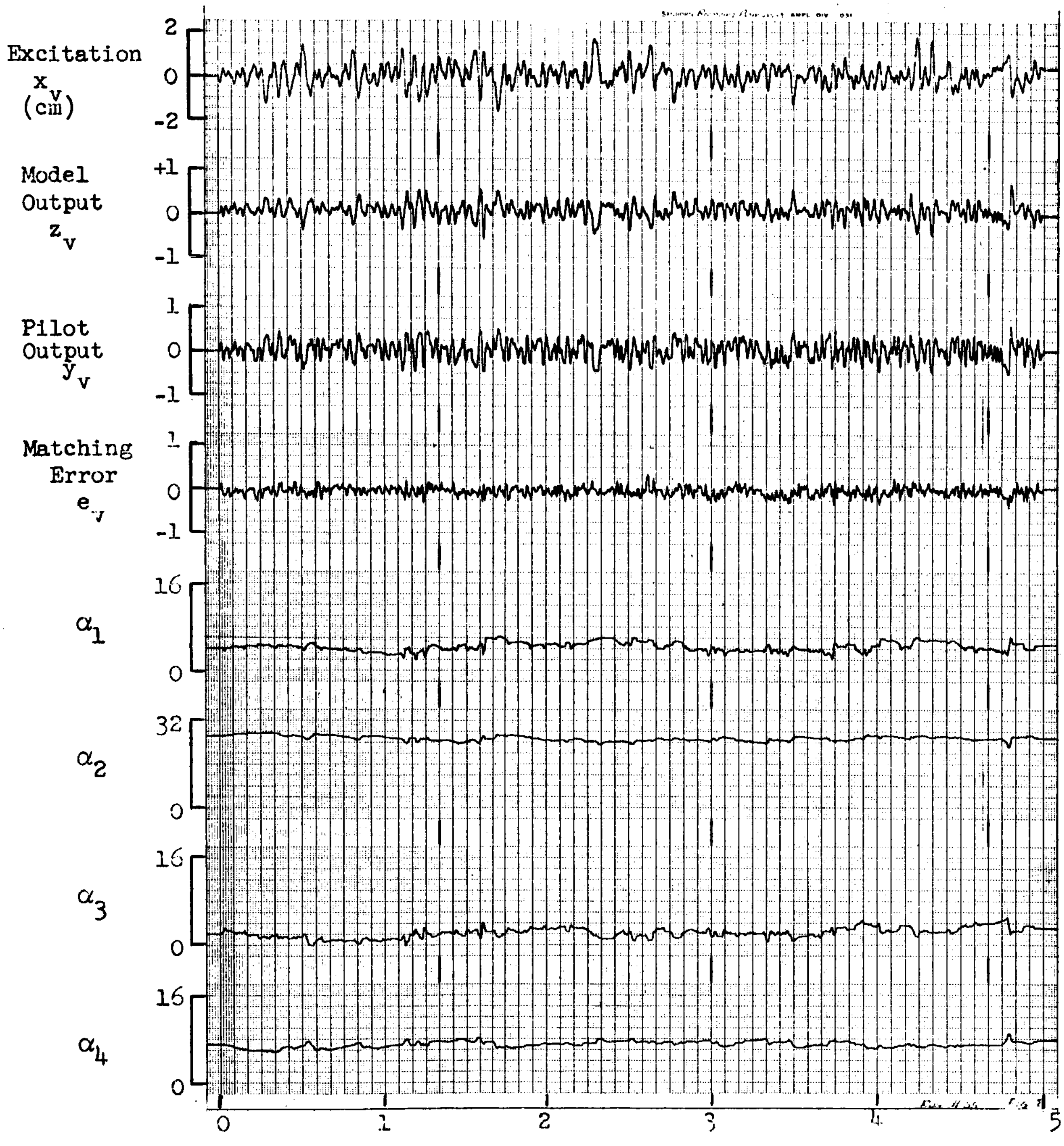


Figure 2

Time History of Parameter Adjustment

Pilot R, Horizontal Axis

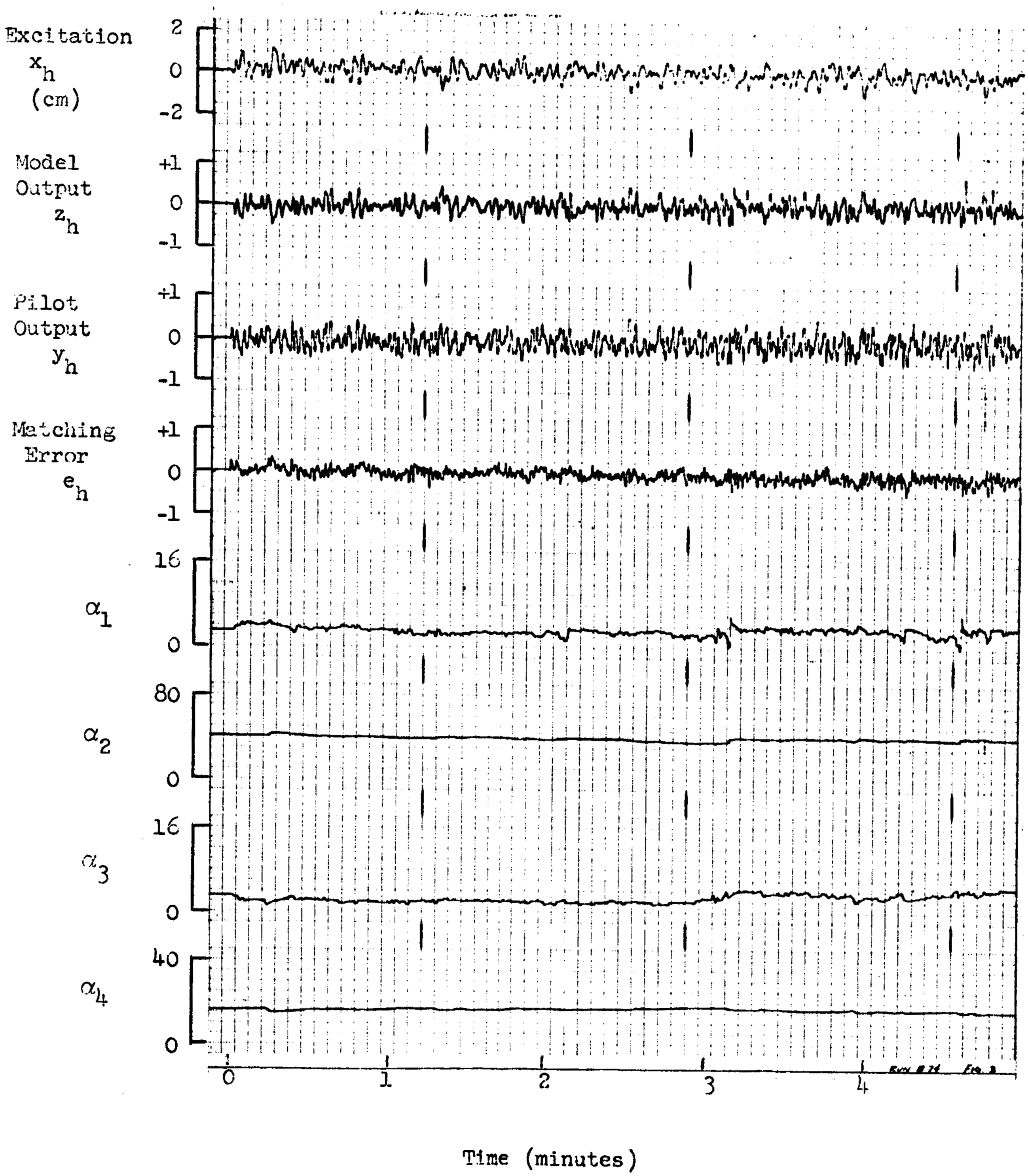


Figure 3

fixed at their approximate mean values (as obtained from the tracking record).

TABLE I

Values of Mean Squared Matching Accuracy
in Horizontal & Vertical Axes

	Matching Accuracy		% of Human Power Output Accounted for by Model	
	$\overline{e_h^2}$	$\overline{e_v^2}$	Horizontal	Vertical
Variable Parameters	0.0115	0.0167	-	-
Fixed Parameters	0.0112	0.0180	63.0	82.7

The resulting residual error is approximately the same as that obtained when the parameters are allowed to vary about the mean value. The final columns in Table I list the percentage of human operator output power accounted for by the model. This percentage is computed from the relationship

$$100\% - (\overline{e_h^2} / \overline{y_h^2}) \times 100 \; . \qquad (5.3)$$

Since the model does, in fact, account for 82.7 percent of the total output power in the vertical case, and for 63.0 percent in the horizontal case, the model can be considered to be a reasonably good representation of the human pilot's tracking characteristics in the two-axis case.

5.2 Effect of Adjustment Gain and Rate Terms in the Adjustment Loop

In order to obtain a quantitative evaluation of the effect of adjustment gain and adjustment strategy, the residual mean squared error $\overline{e_v^2}$ was recorded under several conditions. The results are given in Table II.

TABLE II

Effect of K and q on Model Matching Accuracy

Gain, K	q	$\overline{e_v^2}$
0	0	0.0095
0.5	0	0.0092
1	0	0.0098
2	0	0.0122
0.5	.5	0.0088
0.5	1.0	0.0098

It can be seen that an increase in the adjustment gain will in fact result in a model which produces a poorer match to the human pilot's output than that obtained with low values of gain. This result is not at all what may be expected on an intuitive basis, but probably is due to the considerably larger parameter excursions about the true values which result from increases in adjustment gain. The integrated effect of the parameter excursions results in an overall mean residual error which is larger than the one obtained with small parameter excursions. For comparison the results of a run made with fixed parameter values is also included, under the heading of zero gain. It can be seen that this case yields a relatively low value of residual error, approximately comparable to that obtained when the adjustment gain is set at K = 1. It should be noted that the parameter values used in this run were determined by visual inspection of the tracking record and are not necessarily the true averages.

Previous task reports (References 1, 2, 3) have indicated that the addition of a rate term $q\dot{e}$ in the criterion function contributes significantly to the stability of the adjustment loop. In order to obtain a quantitative measure of the effect of the rate term several runs were made and the residual mean squared error was evaluated. The criterion function was of the form

$$f = (e + q\dot{e})^2 \tag{5.4}$$

and the value q = 0.5 was chosen. (This value of q gave optimum performance in previous studies.) The results are also indicated in Table II and show that the addition of the rate term results in a small but consistent reduction in the residual mean squared error. Since the effect of the q term is to decrease the oscillations of the parameters about their true values by increasing stability of the adjustment loop, the observed improvement is consistent with the preceding comments on the effect of the adjustment gain.

5.3 Comparison of Tracking Performance and Model Matching in One and Two Axes

An extensive number of measures of tracking performance were taken during the model matching runs in order to evaluate quantitatively the differences between operator performance in single axis and in two-axis tasks. As discussed in the previous section the two subjects were first asked to perform single axis tracking of horizontal and vertical motions of the display dot on the oscilloscope screen. The same subjects subsequently performed two-axis tracking tasks, and a comparison of the performance between these two situations was highly desirable. In addition, various measures defining "accuracy of fit" of the mathematical model were determined. The following measures were taken:

1. Mean squared horizontal disturbance input, $\overline{r_h^2}$
2. Mean squared vertical disturbance input, $\overline{r_v^2}$
3. Mean squared horizontal tracking error, $\overline{x_h^2}$
4. Mean squared vertical tracking error, $\overline{x_v^2}$
5. Mean squared horizontal controller output, $\overline{y_h^2}$
6. Mean squared vertical controller output, $\overline{y_v^2}$
7. Mean squared residual matching errors, $\overline{e_h^2}$ and $\overline{e_v^2}$

The mean squared tracking error in each axis can be used to evaluate the ability of the operator to perform the tracking task, while the mean squared residual matching error can be used to evaluate the degree to which the mathematical model

$$\ddot{z} + \alpha_1 \dot{z} + \alpha_2 z = \alpha_3 \dot{x} + \alpha_4 x \tag{5.5}$$

serves to represent the pilot's performance. A tabulation of all the measures listed above as well as the values of the 4 model parameters obtained for each tracking run is given in Table III.

TABLE III

Flight No.	Operator	Run Length T	$\overline{x_H^2}$	$\overline{x_V^2}$	$\overline{r_H^2}$	$\overline{r_V^2}$	$\overline{e^2}$	$\overline{y_H^2}$	$\overline{y_V^2}$	Match %	a1	a2	a3	a4
1	H	305	0	0.258	0	19.2	0.0196	0	0.0805	75.6	6.40	26.00	4.40	6.40
2	R	300	0	0.223	0	23.2	0.0107	0	0.0825	87	6.00	26.00	4.00	8.00
3	H	308	0	0.279	0	16.4	0.0212	0	0.0971	78	6.00	28.00	4.00	8.00
4	R	303	0	0.187	0	16.5	0.0111	0	0.0915	87	6.60	28.00	5.60	10.40
5	H	308	0	0.213	0	19.6	0.0190	0	0.0972	80.5	5.00	28.80	5.00	10.00
6	R	304	0	0.191	0	21.3	0.0132	0	0.0997	86.7	5.00	26.00	5.00	10.40
7	H	304	0.104	0	10.8	0	0.0167	0.0390	0	57	5.60	28.80	4.00	10.40
8	H	306	0.100	0	11.1	0	0.0170	0.0448	0	62	4.80	30.00	4.00	10.80
9	H	305	0.080	0	12.3	0	0.0205	0.0487	0	58	6.00	34.00	6.00	12.40
10	R	303	0.150	0	8.1	0	0.0113	0.0485	0	76.8	4.00	30.00	3.00	12.40
11	R	301	0.114	0	11.9	0	0.0127	0.0460	0	72.4	5.00	28.80	4.40	11.20
12	R	302	0.084	0	11.6	0	0.0151	0.0521	0	71.1	5.60	32.00	5.00	12.00
13	H	297	-	0.316	-	11.6	0.0122	-	0.0600	79.6	4.00	34.00	2.00	9.00
13	H	-	0.153	-	11.0	-	0.0190	0.0594	-	68	3.60	36.00	2.40	14.00
14	R	301	-	0.237	-	10.9	0.0141	-	0.0613	77	3.40	32.80	1.60	9.00
14	R	-	0.131	-	7.20	-	0.0199	0.0461	-	57	2.80	26.00	2.40	14.00
15	H	305	-	0.176	-	15.9	0.0176	-	0.0735	76	7.00	28.00	5.00	14.00
15	H	-	0.113	-	8.7	-	0.0233	0.0880	-	73.5	5.00	36.00	5.00	20.00
16	R	301	-	0.25	-	11.2	0.0112	-	0.0650	82.7	4.00	26.00	2.00	7.00
16	R	-	0.115	-	5.95	-	0.0180	0.0486	-	63.0	3.00	40.00	3.00	16.00
17	H	301	-	0.179	-	13.8	0.0145	-	0.0718	79.8	5.00	32.00	4.00	9.00
17	H	-	0.101	-	10.2	-	-	0.0860	-	-				
18	R	300	-	0.284	-	24.5	0.0197	-	0.0858	77	4.00	32.00	2.00	9.00
18	R	-	0.113	-	11.5	-	0.0170	0.0687	-	75.2	4.00	36.00	5.00	15.00

Mean Squared Values for Single and Two-axis Tracking

TABLE IV

Comparison of Mean Squared Matching Accuracy
for One and Two-axis Tasks

	Operator	Normalized Mean Square Tracking Error		Mean Parameter Values				Axis	K
		Horiz.	Vert.	α_1	α_2	α_3	α_4		
Single Axis	H	.0083	.0136	5.8	27.6	4.2	8.0	v	.29
				5.4	30.8	4.6	11.2	h	.36
	R	.011	.0099	5.6	26.0	4.8	9.6	v	.37
				4.8	30.0	4.2	11.8	h	.39
Two-axis	H	.0122	.0163	5.3	31.4	3.68	8.6	v	.27
				4.3	36.0	4.7	17.0	h	.47
	R	.0146	.0166	3.8	30.3	1.9	8.4	v	.28
				3.27	36.3	3.5	15.0	h	.41
Percent Increase	H	47%	20%						
	R	33%	67%						

The differences between performance in the one and two-axis tasks respectively can be seen most clearly by averaging mean squared tracking error values obtained from the various runs in Table III. The tabulation of these averaged values is given in Table IV. An examination of Table IV reveals a significant increase in normalized mean squared tracking error for both operators in the two-axis task as compared with single axis tracking. Normalized performance measures

$$\left[\overline{x_h^2}\right]_n = \frac{\overline{x_h^2}}{\overline{r_h^2}} \qquad \left[\overline{x_v^2}\right]_n = \frac{\overline{x_v^2}}{\overline{r_v^2}}$$

are obtained by using the total power in the input signal as a normalizing factor. The use of such a normalizing factor is consistent with previous work published in the literature (see for example Elkind, Ref. 7). The increase in normalized mean squared tracking error ranges from 20 to 67 percent, and provides a quantitative measure of the increase in the difficulty of the task experienced by the operators when the second axis is added to the tracking task.

Average values of the parameters obtained from the model matching for both axes and both operators are also included in Table IV. A remarkable consistency between the values of the parameters obtained in a particular axis is observed when comparing the tracking of the two operators, i.e., the α's obtained for the vertical axis from both operators H and R are approximately equal. Likewise, the horizontal axis results for both operators are in close agreement. In view of the rather wide differences in normalized mean squared tracking error between the operators this consistency in the models is particularly interesting since it indicates that the variation in tracking performance cannot be described completely by the linear time-varying mathematical model assumed in this study.

Asymmetry between performance in the two axes is revealed by the degree to which a mathematical model is capable of representing a pilot's performance in each axis. Table V lists $(\overline{e_h^2})$ and $(\overline{e_v^2})$ obtained for both operators normalized with respect to the mean squared tracking error in each case. Input mean squared tracking error rather than the disturbance input were used as normalizing factors in this case since the tracking error is in fact the input signal to both pilot and model in the model matching configuration of Figure 1. Table V also lists values of $(\overline{e_h^2})_n$ and $(\overline{e_v^2})_n$ averaged among all runs for both operators in the respective axes. It shows in addition the fraction of the operator's output not accounted for by model matching. It can be noted that $(\overline{e^2})_n$ is considerably smaller in the vertical axis than in the horizontal axis, both in single axis tasks

TABLE V

Comparison of Normalized Matching Accuracy
for Two Operators

Operator	$(\overline{e_h^2})_n$	$(\overline{e_v^2})_n$	
H	.19	.080	One-axis
R	.112	.060	
H	.172	.067	Two-axis
R	.150	.058	
$(\overline{e^2})_n$ Average of Two Operators			
One-axis	.150	.070	
Two-axis	.160	.062	
Percent of Total Operator Output Power Not Matched by Model $\frac{\overline{e^2}}{\overline{y^2}}$			
Operator	Horiz.	Vert.	
H	41.0	21.7	One-axis
R	27.0	12.7	
H	27.2	21.6	Two-axis
R	33.6	21.2	

and for the vertical axis of the two-axis task. In other words the mathematical model of Equation (4.1) represents a human operator's performance in the vertical axis more satisfactorily than in the horizontal axis. The causes of this lack of symmetry in the performance of the two tasks require further investigation. A controlled experiment may be required in order to isolate pertinent effects (such as mismatch between design characteristics of the two axes of the hand controller) which might contribute to and provide an explanation of the asymmetry. This result is confirmed also by a comparison of the values $\frac{\overline{e_h^2}}{\overline{y_h^2}}$ and $\frac{\overline{e_v^2}}{\overline{y_v^2}}$ which represent the fraction of the total operator's output which is not matched by the model. Once again this fraction is smaller for the vertical axis than for the horizontal axis.

5.4 Cross Coupling Between Axes

As discussed in Section 2, two types of cross-coupling between axes were considered. Perceptual (or input) cross-coupling terms are given on the right hand side of Equation (2.4) and motor (or output) cross coupling terms are given on the left hand side of Equation (2.4). An extensive visual search of the tracking records for each run of the two-axis task was made to identify possible cross-coupling effects between the perceptual input in the vertical axis on the motor output in the horizontal axis (and vice versa). Such an examination of the tracking record would reveal disturbances in the horizontal output resulting from a disturbance in the vertical input when no such disturbance appears in the horizontal input. Evidence of such cross-coupling terms can be seen in Figure 4 and is indicated by arrows. After finding tracking records which show this type of cross-coupling, the corresponding terms were introduced into the model, and parameter matching was performed over the entire length of the tracking run. The resulting values of $\overline{e_h^2}$ were compared with the value of $\overline{e_h^2}$ obtained when no cross-coupling terms were employed. It was anticipated that this comparison would yield evidence of the existence of cross-coupling terms of the form

$$\beta_1 y_v, \quad \beta_3 x_v, \text{ and } \beta_4 \dot{x}_v$$

in the horizontal model. However, the resulting tracking records did not show clearly defined or consistent values of the cross-coupling terms for

Time History of Human Pilot Tracking
Two-axis Task
Pilot R

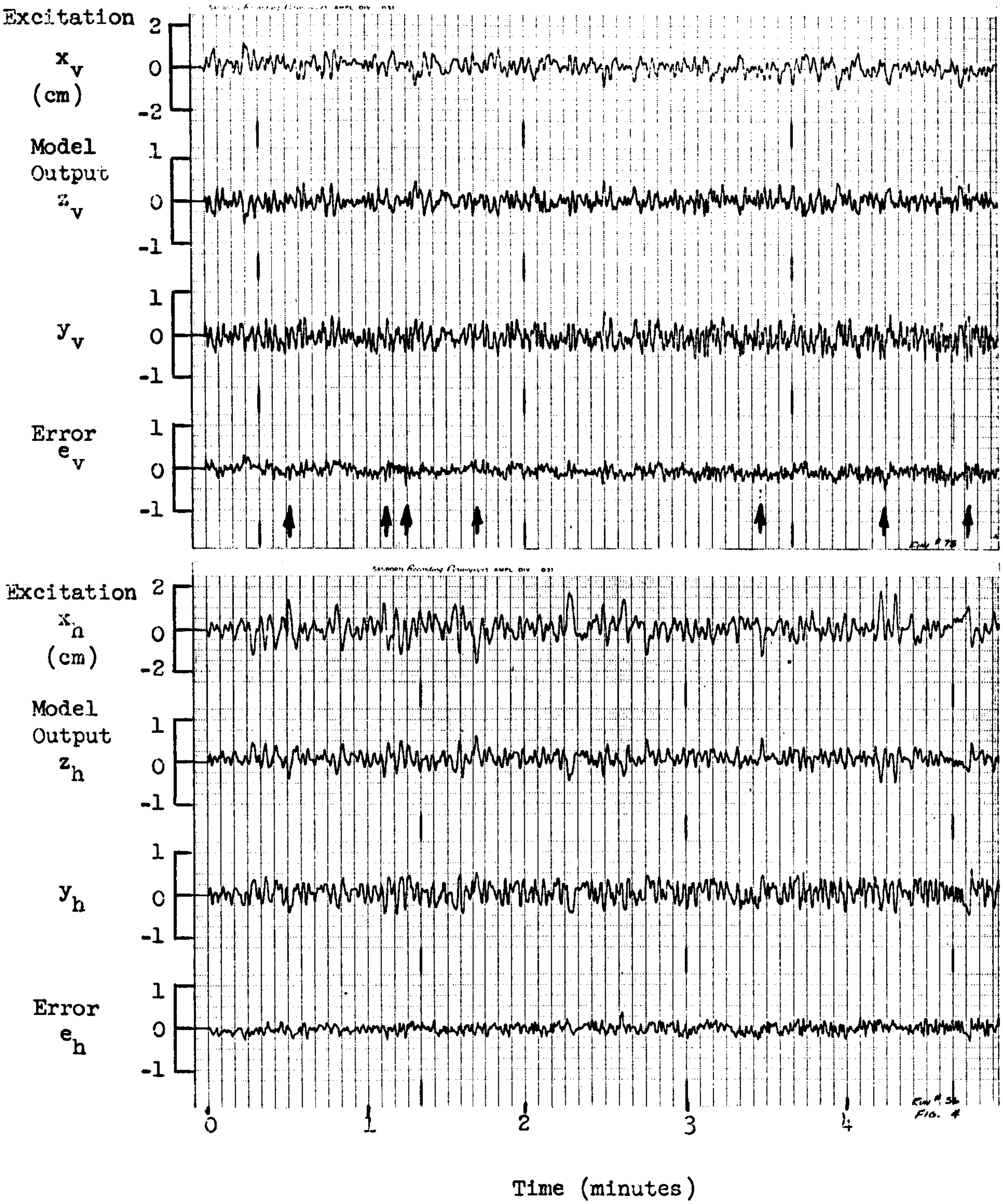


Figure 4

the entire length of the tracking record. A typical record of the measured cross coupling coefficient β_3 is shown in Figure 5. The corresponding value of the mean squared residual error actually shows a slight increase as a result of introducing the β_3 cross coupling term into the mathematical model. Similar results were observed for the β_1 and β_4 cross coupling terms. In general, the introduction of the cross coupling terms appeared to be detrimental to overall model matching in terms of residual mean square error. It should be noted that during the search for cross coupling terms, the α parameters were held fixed at their average values in order to eliminate possible interaction of the adjustment loops.

5.5 Cross Coupling as a Temporary or Short Duration Phenomenon

While searching for consistent cross coupling terms some of the tracking records indicated values of β which remained approximately constant for periods ranging from 20 to 60 seconds. A typical run showing this effect is given in Figure 6. An examination of Figure 6 reveals that the cross coupling coefficient β_3 has a reasonably constant value extending from $t_1 \cong 130$ seconds to $t_2 \cong 204$ seconds at values between 1.2 and 1.6 units. The effect of introducing the cross coupling term into the model of the human operator during this interval results in approximately 9.2% reduction in $\overline{e^2}$ as shown in Table VI. This decrease of $\overline{e^2}$ due to the introduction of a cross coupling term into the mathematical model indicates the existence of cross coupling for short periods of time. Similar reductions

TABLE VI

Effect of Cross Coupling Term βx_v
on Model of Horizontal Axis Response

Run	β_3	$10\int_{t_1}^{t_2} e^2\,dt$	t_2-t_1	$\frac{10}{t_2-t_1}\int_{t_1}^{t_2} e^2\,dt$	Ave.	Dif.	%
1	0	14.59	74	.1972			
2	0	14.49	74	.1958	.1961		
3	0	13.69	70	.1955		.0180	9.18
4	1.6	12.79	72	.1776			
5	1.6	12.60	73	.1726	.1781		
6	1.6	13.63	74	.1841			

$t_1 = 131$ sec $\qquad t_2 = 207$ sec

Time History - Adjustment of Parameter β_3

Pilot R

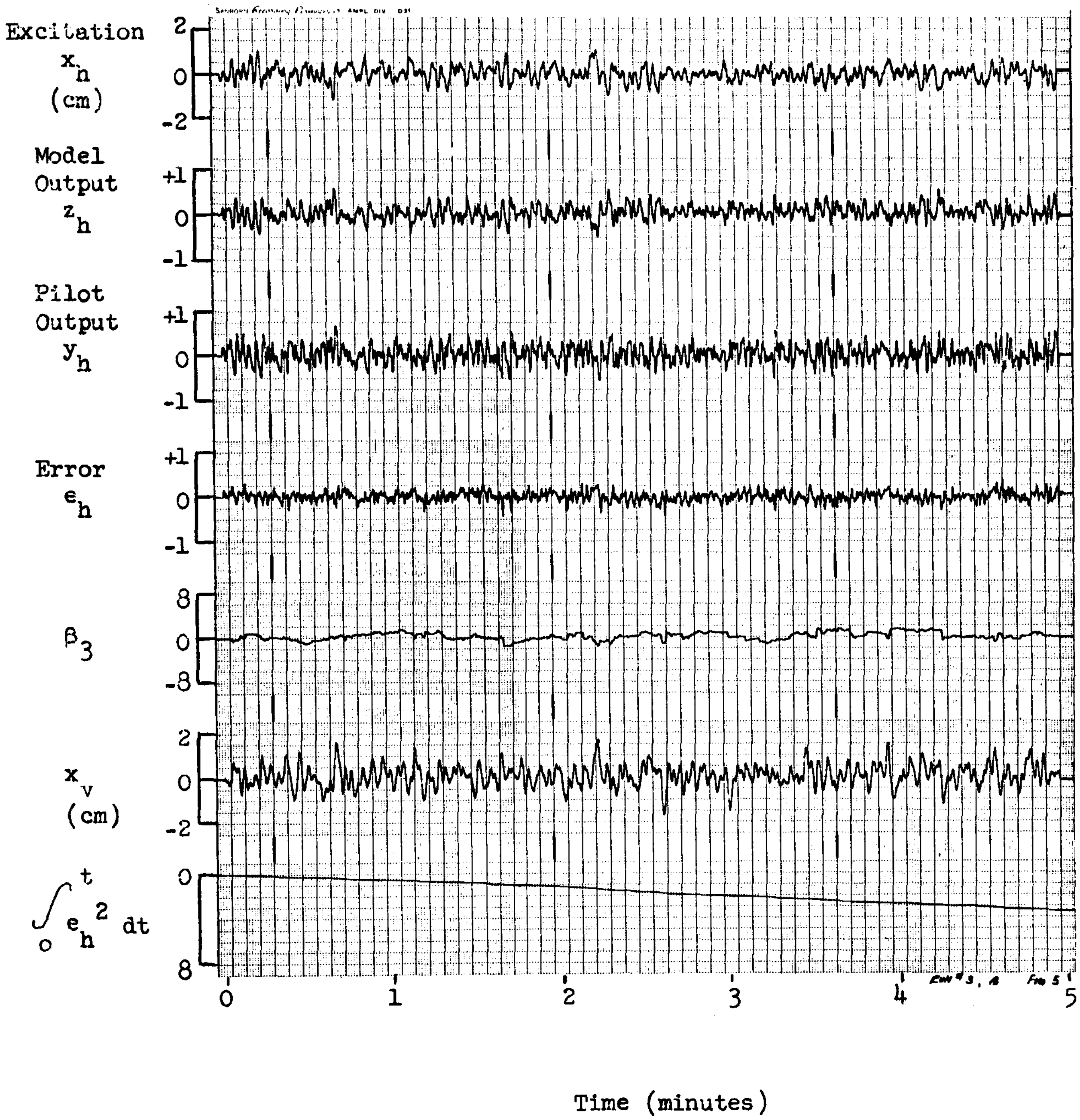


Figure 5

Time History - Adjustment of Parameter β_3
Pilot R

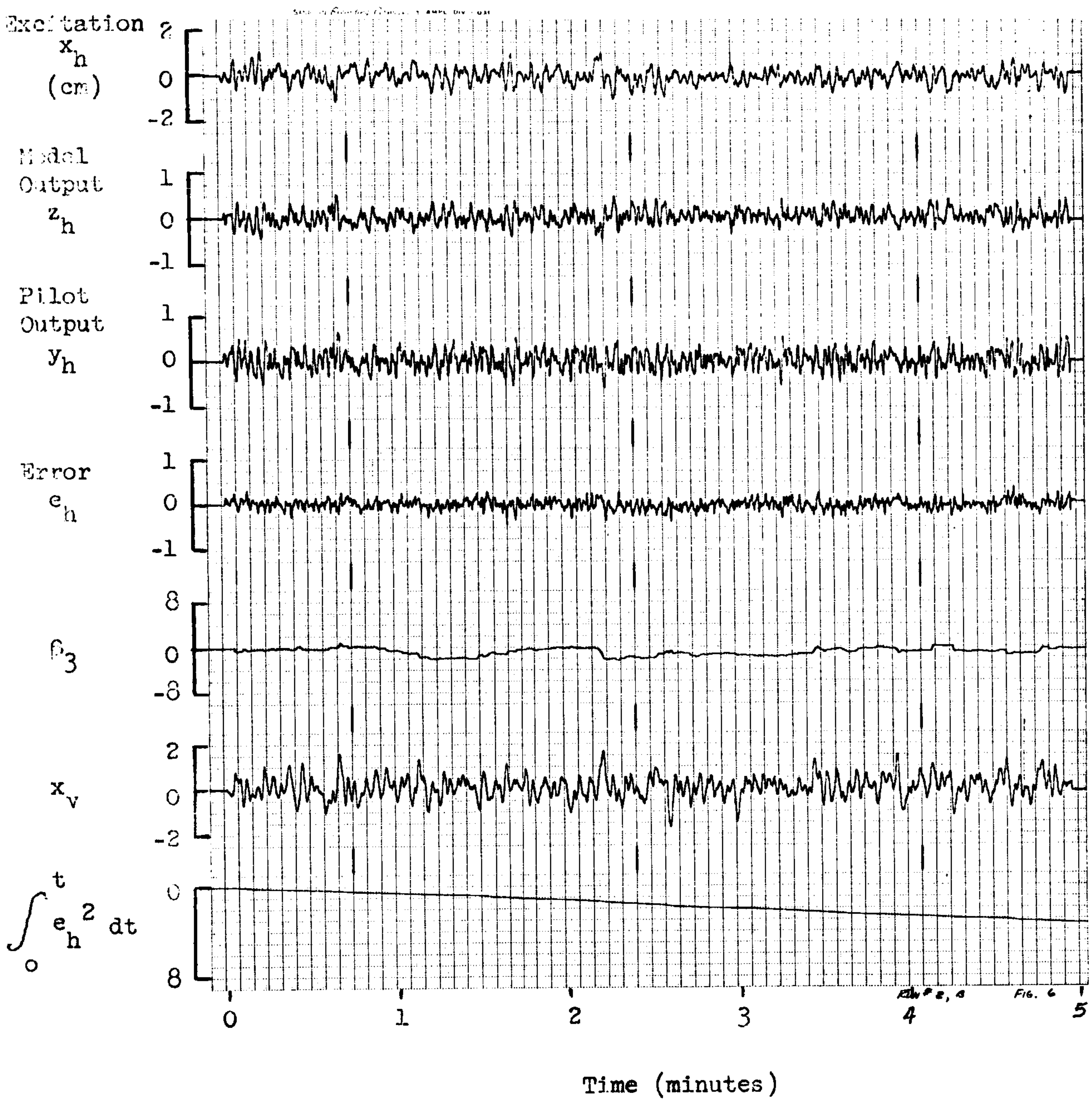


Figure 6

of $\overline{e^2}$ were observed for other short duration runs.

In summary it should be emphasized that the existence of cross coupling between axes was established by using a measure obtained from the residual matching error. Consequently, the model matching technique used in this study is suitable for detection and quantitative determination of cross-coupling which occurs in the responses of the human operator in two-axis tracking. It is surmised from these results that the technique can yield new data on the existence of systematic cross-coupling in realistic tracking situations where cross-coupling between operator responses is caused by the dynamic characteristics of the controlled element. The task studied here did not include conditions which would evoke a more consistent coupling in operator responses. Additional research along these lines should be of great interest.

5.6 Closed-loop Characteristics of Human Dynamic Response

The closed-loop stability of the model was examined for a single axis task and one axis of the two-axis task. Results showed only a minor shift in the closed-loop poles with little effect on system stability.

The human dynamic response equation obtained from a typical single-axis tracking run is given by

$$G_1(s) = \frac{Z}{X} = \frac{.29\ (.525\ s + 1)}{(.036\ s^2 + .21s + 1)}$$

whereas a typical case of two-axis tracking yielded

$$G_1(s) = \frac{Z}{X} = \frac{.269\ (.286\ s + 1)}{(.0385\ s^2 + .154\ s + 1)} .$$

In both tasks the controlled element dynamics was characterized by

$$G_2(s) = \frac{10}{s\ (s + 1)} .$$

The resulting characteristic equations of the closed-loop system are

$$.036s^4 + .246\ s^3 + 1.21\ s^2 + 1.52\ s + 3.9 = 0$$

for the single axis case, and

$$.0385\, s^4 + .1925\, s^3 + 1.154\, s^2 + 1.769\, s + 2.69 = 0$$

for the two-axis case.

The closed loop poles obtained from these characteristic equations are given below:

Single-axis Task (vertical)	Two-axis Task (vertical axis)
$s_1 = -1.55 + 4.0j$	$s_1 = -1.67 + 4.29j$
$s_2 = -1.55 - 4.0j$	$s_2 = -1.67 - 4.29j$
$s_3 = -.315 + 2.04j$	$s_3 = -.83 + 1.62j$
$s_4 = -.315 - 2.04j$	$s_4 = -.83 - 1.62j$

It is interesting to observe that both pairs of complex roots exhibit negative real parts, in agreement with the stable performance evidenced in all single and two-axis human tracking experiments performed in this study. Other researchers in the field have frequently obtained unstable roots from parameter identification studies of two-axis tracking data that appeared stable on inspection.* Such a discrepancy did not arise here. A more comprehensive investigation of this point would be very desirable.

A comparison of the above open-loop and closed-loop characteristics of human operators with results reported by Adams (Reference 6, p. 10-12) indicates the following similarities and differences:

Open-loop Response

1) The operator's gain is 4 to 8 times larger in Adams' results, probably to be explained by the fact that his controlled element gain is 5 times smaller; the operators tend to compensate for it by increased gain.
2) Lead compensation time constants found in STL's study fall within the average range of those reported by Adams (0.2 ... 0.8 sec). Adams' extreme cases of zero lead and

* Verbal communication by Mr. M. Sadoff of NASA Ames Research Center.

extremely large lead (1.2 ... 1.6 sec) are not matched in this study.

3) STL's results for the second order lag yield complex roots in close proximity to the double roots obtained by Adams on the basis of the postulated structure of his mathematical model.

Closed-loop Response

1) The oscillatory modes found in Adams' and STL's study have similar frequencies ranging from 2.0 to 4.0 rad/sec. Adams' damping factor is considerably lower on the average (by a factor of 2 to 5) than STL's.

2) Adams' real-roots are not matched by STL's data, probably in view of the difference in model structure. The complex closed-loop poles of the second oscillatory mode obtained by STL are located far from the real axis in the s-plane. The significance of this difference cannot be explained without a closer comparison of experimental conditions.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The closed-loop model matching techniques which were explored under this research study (Tasks 1 to 3) and applied to two-axis tracking data during the final phase (Task 4) covered in this report have proved to be effective in yielding useful descriptions of the human operator and consistent parameter values of his tracking performance.

In general, these parameters exhibit variations with time which are traceable (1) to high peaks in the random excitation signal, (2) to dynamic interactions between parameter adjustment loops, and (3) probably to a large extent to fluctuations in the operator's output which are not represented in the "deterministic" second-order mathematical model employed here. Actually, the operator generates spurious output components which may best be described in statistical terms. In the literature on human operator models the unmatched component is referred to as remnant term and is analyzed on a statistical basis. Operator variability over extended periods of tracking operation and over ensembles of repeated trials, as well as distributions of parameters over ensembles of pilots having similar training and proficiency should be further analyzed in this sense.

It was found in the two-axis tracking study that operator training must be a carefully controlled experimental variable in order to derive meaningful parameter values. The two-axis tracking study by Humphrey (Reference 4) has determined quantitative data on operator performance as a function of training time and provided a basis for adopting an adequate training standard in performing Task 4. The study by Adams (Reference 6) showed in turn that inadequate training of the operators may lead to misinterpretation of the nature of parameter variations observed during the tracking tests.

The present study has not been oriented primarily toward providing data on human tracking performance in general, but rather toward developing and exploring computer methods which promise to be suitable for this purpose. Task 4 has provided the means of dealing with multi-axis situations and has given insight into the nature of inter-axis coupling. It will be most interesting to pursue further studies aimed at deriving comprehensive human operator models, including cases of linear and nonlinear performance, with and without essential cross-coupling, in realistic-type tracking and vehicle control situations. For such a purpose the use of two simple, identical, and uncoupled control channels each characterized by K/s(s+1) as was done in this study would be too unrealistic. An extension of the studies to such tasks as instrument landing in terms of aircraft longitudinal dynamics with lift and thrust being the controlled variables would be highly interesting and desirable.

Another aspect of great significance which should be explored in multi-axis studies is the nature of the reception and interpretation of displayed stimuli by the human pilot. Clearly, the presentation of specific stimuli such as vertical and horizontal dot excursions on an integrated display instrument is an idealization seldom encountered in practice. The stimuli received may be more diffuse, including visual cues from flight instruments and from the extra-vehicular scene, plus kinesthetic feedback stimuli. The significant effect of additional motion cues in altering pilot tracking performance has been demonstrated by the interesting results of Adams' study (Reference 6). Practical considerations of vehicle control must be included in plans for further studies, with emphasis on clear definition of pilot input stimuli and their representation in the mathematical model structure.

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